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VORTEX FLOW IN TWIST EXTRUSION

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ВИХРЕВОЕ ТЕЧЕНИЕ МЕТАЛЛА ПРИ ВИНТОВОЙ ЭКСТРУЗИИ

Twist extrusion (TE) is a metal forming technique for processing long metallic products by simple shear. This allows producing microstructures and textures of the billets radically different from those produced by conventional extrusion. The current study aims at investigation of vortex flow in TE that previously received little attention in the literature. Particularly, the mechanism of the vortex flow and its effects on the microstructure at different scales are elucidated.
For the experimental study of the kinematics of the flow of material workpieces of twist extrusion processed was used improved method of plasticity theory. According them the latter lies in the fact that to determine the stress-strain state of the workpiece is used kinematically admissible velocity fields with variable parameter determined by identifying the criterion of best fit lines of current theoretical and experimental.
Prospective applications of vortex flow in TE are also discussed.
Keywords: *twist extrusion, simple shear, vortex flow, mixing*

Introduction

Conventional extrusion processes usually change cross sectional dimensions of semiproducts. In this sense, twist extrusion (TE) is not a conventional extrusion technique because the billet does not change its cross section during the process. Similar to other severe plastic deformation techniques, the primary use of TE is aimed at improving properties of metallic materials through producing special ultrafine grained microstructures [1].

Another critical difference between the TE and conventional extrusion processes lays in their main deformation modes: simple shear in TE instead of elongation in the conventional ones. Simple shear was reported in many works to be quite a distinct deformation mode in terms of microstructure formation [2-4]. For this reason, there is continuous interest in metal forming techniques based on the use of simple shear: high-pressure torsion [5], equal channel angular pressing [6], shear extrusion [7], torsion extrusion [8] as well as processes emerged from the concept of TE [9-11]. All of these methods allows for producing ultrafine grained structures in metallic materials, which are known for improved and sometimes unique properties [12].

The current study reviews and discusses some features of metal flow during TE, particularly, the fact that deformation in TE is uniquely associated with vortex flow, which provides wide opportunities for microstructure formation at different scales.

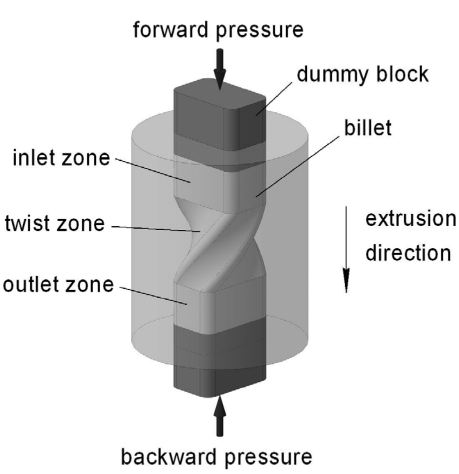


Fig. 1. Schematic of the TE process

The principle of twist extrusion and kinematics of plastic flow

The principle of TE is to extrude a billet through a die that has a so-called twist zone between straight inlet and outlet channels (Fig. 1).

The surface of the twist zone is formed by the die profile “swept” along a helix line. Such geometry of the die channels allows the workpiece to well preserve its initial shape well.

When a workpiece is extruded through a TE die sketched in Fig. 1, the metal is subject to plastic deformation. During the TE process, the main deformation mode is simple shear that takes place at the transients between the twist and straight channels [1]. The strain rate, accumulative von Mises strain and its distribution in the processed bar is determined by the geometry of the TE die: height of the twist zone, pitch of the twist surface, and dimensions of the transverse profile. The von Mises strain accumulated during one TE pass is approximately 1.0 [13].

Owing to the little change in the shape of the workpiece during TE, the process can be repeated for accumulation of large strains. At relatively low homologous temperatures, TE leads to intensive grain refinement accompanied by formation of deformation-induced high-angle grain boundaries. As a result, TE can be used to form ultrafine grained structures, which are characterized by physical and mechanical properties significantly different from those in coarse grained structures.

Kinematics of flow during TE was analyzed in the paper that introduced the TE process [14]. It was shown that the total metal flow during TE can be considered as a sum of two components: so-called helical flow and deviations from helical flow. Herein, helical flow denotes ideal tool-controlled motion of a virtual rigid plane (remaining plane during TE) normal to the extrusion direction. As a result of such ideal helical flow, material points of each virtual plane preserve their relative locations and move together in the extrusion direction. Deviations from ideal helical flow are termed as cross flow; these deviations result in planar flow within the virtual planes of the sample. In contrast to helical flow, cross flow leads to displacement of the material points from their relative locations within the planes normal to the extrusion direction.

Mathematically the decomposition of the total metal flow into the two components can be shown by considering velocity fields. The velocity field of total metal flow $\vec{V}$ [14] is decomposed as

$$\vec{V} = \vec{V}_1 + \vec{V}_2 , \tag{1}$$

where $\vec{V}_1$, $\vec{V}_2$ denote velocity fields of helical flow and cross flow, respectively.

Below the velocity field in Eq. 1 is shown to lead to vortex flow of metallic materials at different scales, which opens new routes to tailored microstructures.

Helical flow and vortex flow at the micro scale

Consider a Cartesian coordinate system xyz whose z axis is arranged along the symmetry axis of a rectangular te die, while x and y axes are parallel to the sides the die profile. The velocity field of helical flow is then defined by the components [14]

$$V_{1x} = -\frac{yV_0 \tan\beta}{R},\; V_{1y} = \frac{xV_0 \tan\beta}{R},\; V_{1z} = -V_0 , \tag{2}$$

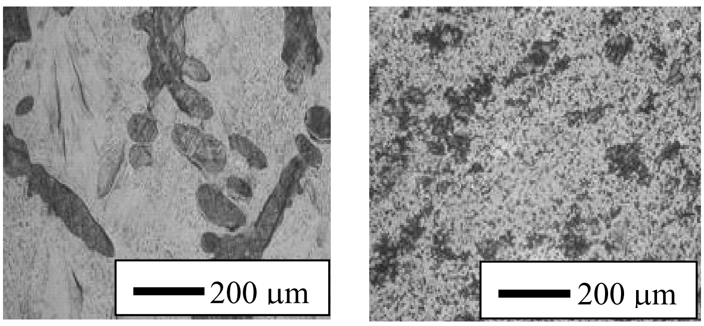
where β is the slope angle of the twist line, V_0 is the speed of the billet along z axis, and R is the radius of the circle circumscribing the rectangle of the die profile.

When the components are known, the velocity field of helical flow $\vec{V}_1$ reduces to the following velocity gradient tensor

$$\frac{d\mathbf{V}_1}{d\mathbf{r}} = \begin{pmatrix} 0 & 0 & -\dfrac{yV_0}{R\cos^2\beta}\dfrac{d\beta}{dz} \\ 0 & 0 & \dfrac{xV_0}{R\cos^2\beta}\dfrac{d\beta}{dz} \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & -\dfrac{V_0 \tan\beta}{R} & 0 \\ \dfrac{V_0 \tan\beta}{R} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \tag{3}$$

The first term in Eq. 3 shows the presence of simple shear at the transient planes between the twist zone and the straight channels because only at the transient zones $d\beta/dz \neq 0$. The second term in Eq. 3 describes rigid body rotation around z axis.

According to the previous works [2, 15], in metallic materials large simple shear strains cause vortex flow at a scale with a characteristic dimension of 10 μm. This vortex flow is similar to the turbulent flow in fluids. Vortex flow at this scale leads to intensive mass transport and mixing of phases in the material (Fig. 2).



a *b*

Fig. 2. Microstructures of phosphorous-copper alloy (8.5% wt. of P) before (a) and after (b) two passes of twist extrusion (extrusion temperature 100 °C, back pressure 200 MPa)

Cross flow and vortex flow at the macro scale

Cross flow is defined as deviations from the ideal tool-controlled flow. The main features of cross flow were analyzed for titanium in work [16] by using a flow visualization technique and numerical simulations. Samples of commercially pure titanium were twist-extruded through a die of a rectangular profile (Fig. 3) at 350 °C with back pressure of 200 MPa.

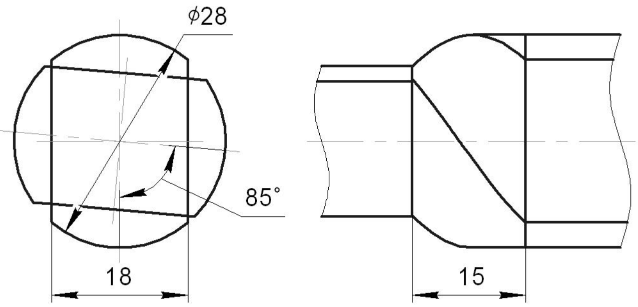


Fig. 3. Design of the die used in the experimental studies of titanium flow during TE

For visualization of metal flow during TE, copper fibers were embedded into the titanium samples as shown in Fig. 4.

Fig. 4. Visualization of metal flow during TE: a) a sketch of the sample with embedded copper markers before TE; b) photographs of the sample cross sections with markers before and after TE

Metallurgical sectioning and optical analysis of the sample cross sections allowed tracking marker coordinates. For the titanium sample shown in Fig. 4b, coordinates of initial (x, y) and deformed (x', y') markers are listed in Table 1 in terms of the Cartesian coordinate system defined in the previous section.

Table 1

Marker coordinates (mm) before and after one pass of TE. The origin (0,0) is at the center of the cross section

	1	2	3	4	5	6	7	8	9
x	-9,0	0,0	9,0	-9,0	0,0	9,0	-9,0	0,0	9,0
y	6,0	6,0	6,0	0,0	0,0	0,0	-6,0	-6,0	-6,0
x'	-8,1	1,1	9,6	-9,3	0,1	9,3	-9,5	-1,4	7,9
y'	6,0	5,9	4,9	1,0	0,0	-1,5	-4,9	-6,0	-6,4

These experimental results suggest that cross flow during TE can be considered as a mapping that carries material points before TE into points after TE within the planes normal to the extrusion direction. The mapping can be represented in a form of the following equations:

$$x' = f(x, y),\; y' = g(x, y), \tag{4}$$

where functions $f(x, y)$ and $g(x, y)$ are found from the data in Table 1.

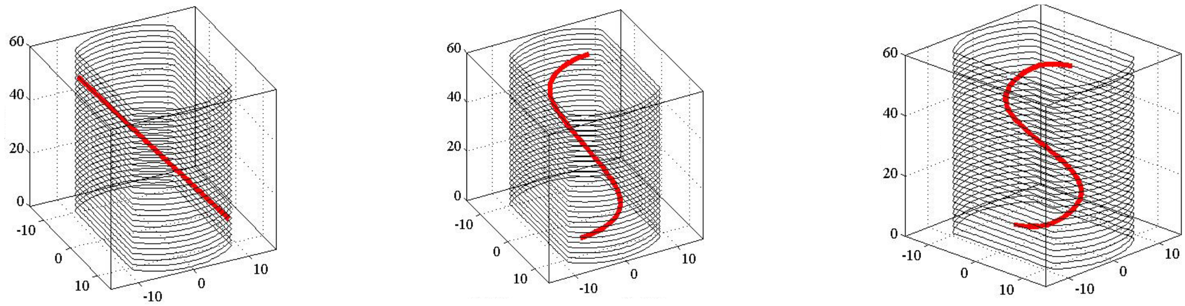
The mapping described by Eq. 4 makes possible tracking any material points during TE. For example, for a material point whose initial position is defined as

$$x = x(z),\; y = y(z), \tag{5}$$

the mapping (one TE pass) can be written in the form of the equations:

$$x' = f(x(z), y(z)),\; y' = g(x(z), y(z)), \tag{6}$$

Eq. 6 provides a solution for the inverse problem: to find the arrangement and shape of an initial manifold of material points needed for a prescribed final arrangement and shape. It follows that, for example, fibers initially inclined in respect to the extrusion axis can form a helical shape after multipass TE [16]. The orientation of the helical fibers is controlled by the die geometry. The ability to form helical fibers during TE provides a route for producing materials with a chiral structure [17]. Based on the data in Table 1, Fig. 5 exemplifies a shape transformation of an inclined fiber as a result of multipass TE.



a *b* *c*

Fig. 5. Shape transformation of an inclined fiber that takes place during multi-pass TE: a – initial arrangement and shape; b – after 3 passes; c – after 5 passes

Finally, considering TE as a mapping supported by marker techniques (e.g. coordinates in Table 1) makes it possible to predict formation of vortex microstructures which were observed experimentally in Fig. 6.

a *b*

Fig. 6. Vortex structure formed by TE: a point set after seven transformations described by Eq. 4; and (b) microstructural traces of vortex flow in aluminum after 4 TE passes [18]

Formation of vortex structure is accompanied by significant mixing of the material [19]. In TE, mixing can be further intensified by rotating the billet 180° around its axis after every 5–7 passes, which results in periodical change of the vortex direction. Moreover, during TE the material near surface periodically flows into the billet volume while some inner material emerges. Owing to these counter flows, multipass TE provides prerequisites for mechanical alloying [20]. By the virtue of the mentioned mixing effect, performing TE in surface-active media grants surface treatment of the material for further improvement of its properties (e.g. surface hardening).

Summary

In twist extrusion deformation of metallic materials is accompanied by vortex flow that takes place at different scales. Multi-scale vortex flow opens new horizons for tailored microstructure formation and improving properties of materials.

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Аннотация. *Винтовая экструзия (ВЭ) - способ деформирования металлов для обработки длинномерных металлических изделий с помощью простого сдвига. Это позволяет получать микроструктуры и текстуры в заготовках радикально отличающиеся от тех, которые получены с помощью обычной экструзии. Данное исследование направлено на изучение вихревого течения при ВЭ, которому ранее не уделялось достаточного внимания в литературе. В частности, рассматривается механизм вихревого течения и его влияние на микроструктуру на различных уровнях. Для экспериментального изучения кинематики течения материала заготовок при ВЭ использован усовершенствованный метод визиопластичности. Отличие от последнего заключается в том, что для определения напряженно-деформированного состояния обрабатываемой заготовки используется кинематически-возможное поле скоростей с варьируемым параметром, определяемым путем идентификации по критерию наилучшего соответствия теоретических линий тока и экспериментальных. Также предложены перспективы применения вихревого течения в ВЭ.*

Ключевые слова: *Винтовая экструзия, простой сдвиг, вихревое течение, смешивание*

Анотація. *Гвинтова екструзія (ГЕ) – спосіб деформування металів для обробки довгомірних металевих виробів за допомогою простого зсуву. Це дозволяє отримувати мікроструктури і текстури в заготовках кардинально відмінні від тих, що отримані за допомогою звичайної екструзії. Представлене дослідження направлене на дослідження вихрової течії при ГЕ, якій раніше не приділялося достатньої уваги в літературі. А саме: розглядається механізм вихрової течії та її вплив на мікроструктуру на різних рівнях. Для експериментального вивчення кінематики течії матеріалу заготовок при ВЕ використаний удосконалений метод візіопластічності. На відміну від останнього він полягає в тому, що для визначення напружено-деформованого стану оброблюваної заготовки використовується кинематически-можливе поле швидкостей з варійованим параметром, визначальним шляхом ідентифікації за критерієм найкращої відповідності теоретичних ліній струму і експериментальних. Також запропоновані перспективи застосування вихрової течії в ГЕ.*
Ключові слова: *гвинтова екструзія, простий зсув, вихрова течія, змішування*

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